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Statistical Correlation of Observed Ground Motion with Low-Rise Building Damage: Project Rulison, January 1973

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Prepared Under Contract AT(26-1)-99
for the Nevada Operations Office
United States Atomic Energy Commission

JAB

JOHN A. BLUME & ASSOCIATES RESEARCH DIVISION

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STATISTICAL CORRELATION OF OBSERVED GROUND MOTION WITH LOW-RISE BUILDING COMPONENT DAMAGE: PROJECT RULISON

by

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January 1973

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STATISTICAL CORRELATION OF OBSERVED GROUND MOTION WITH LOW-RISE BUILDING COMPONENT DAMAGE: PROJECT RULISON

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ABSTRACT

This report presents the results of a statistical correlation study conducted using observed ground motion and structure damage data obtained from the RULISON underground nuclear explosion gas stimulation experiment.

Statistically derived relationships between pseudo absolute acceleration response spectrum values and damage ratios for the most frequently damaged components of low-rise buildings are given. Results show the relative vulnerability to damage of chimneys, interior walls, exterior walls, and foundations for various spectral intensities. The derived motion-damage relationships and other conclusions given in this report should be applicable to other locations where building characteristics are similar to those of the Project RULISON area.

I. INTRODUCTION

John A. Blume & Associates (JAB) conducts structural response and damage investigations for the Atomic Energy Commission's Nevada Operations Office (Office of Effects Evaluation) to determine the effects of ground motion on a wide variety of structures. The effort described herein is directed toward studying the relationships between ground motion and low-rise building damage that were observed for the RULISON event. These and additional data are being utilized to improve methods for predicting damage to low-rise buildings caused by ground motion.

Project RULISON[1] was a nuclear gas stimulation experiment sponsored jointly by Austral Oil Company Incorporated, Houston, Texas, the U. S. Atomic Energy Commission, and the Department of the Interior, with the program management provided by CER Geonuclear Corporation of Las Vegas, Nevada, under contract to Austral. Its purpose was to study the economic and technical feasibility of underground nuclear explosions to stimulate production of natural gas from the low-permeability, gas-bearing Mesaverde Formation in the Rulison field in western Colorado. The nuclear explosive for Project RULISON was detonated successfully at approximately 3:00 PM Mountain Daylight Time, September 10, 1969, at a depth of approximately 8425 feet below ground level, and was completely contained. Preliminary results indicate that the RULISON device behaved about as expected, i.e., with a yield of approximately 43 kilotons.

A. Background

Prediction of damage to low-rise buildings subjected to ground motion is a necessary step in evaluating the potential damage and hazards for projects requiring the use of underground nuclear explosives. It is also a step toward improving design and construction practices to provide better resistance of buildings to ground motion.

There are two somewhat distinct procedures that may be employed for either predicting or investigating structure damage caused by ground motion: fundamental and technical procedures. The fundamental procedure involves first developing a model of the structure and subjecting it to a ground motion to obtain response, and then comparing appropriate damage criteria with the response to arrive at an effects prediction. Alternatively, the technical procedure more directly involves comparing a ground motion with appropriate damage criteria to arrive at an effects prediction. The fundamental procedure is more applicable for investigations of individual structures; the technical procedure is more applicable to groups of structures. The study described herein was conducted along the lines of the technical method of investigating ground motion - damage relationships.

The RULISON experiment has provided the first good opportunity to obtain the data required to effectively study ground motion and structure damage relationships for low-rise buildings. In a previously reported investigation,[2] RULISON ground motion and structure damage data were statistically studied to obtain motion and damage relationships for the overall structure system without reference to any specific type of damage. In this report, motion and damage relationships are studied for those components of low-rise buildings that were most frequently damaged.

B. Purpose and Scope

The purpose of this report is to present the results of the statistical study conducted to investigate the relationships between ground motion and damage to components of low-rise buildings using appropriate data obtained from the RULISON experiment. The specific building components for which motion-damage relationships are derived are: chimneys, interior walls, exterior walls, and foundations. Window damage is discussed, but because so few windows were broken a motion-damage relationship was not derived.

Because of the paucity of data samples, most conclusions made in this report may not be generalized for definite quantitative damage prediction purposes. However, they serve as the best available guide for comparing relationships between ground motion and damage to various components of low-rise buildings.

II. DATA

To conduct a statistical analysis correlating structure damage with ground motion, three types of information are required:

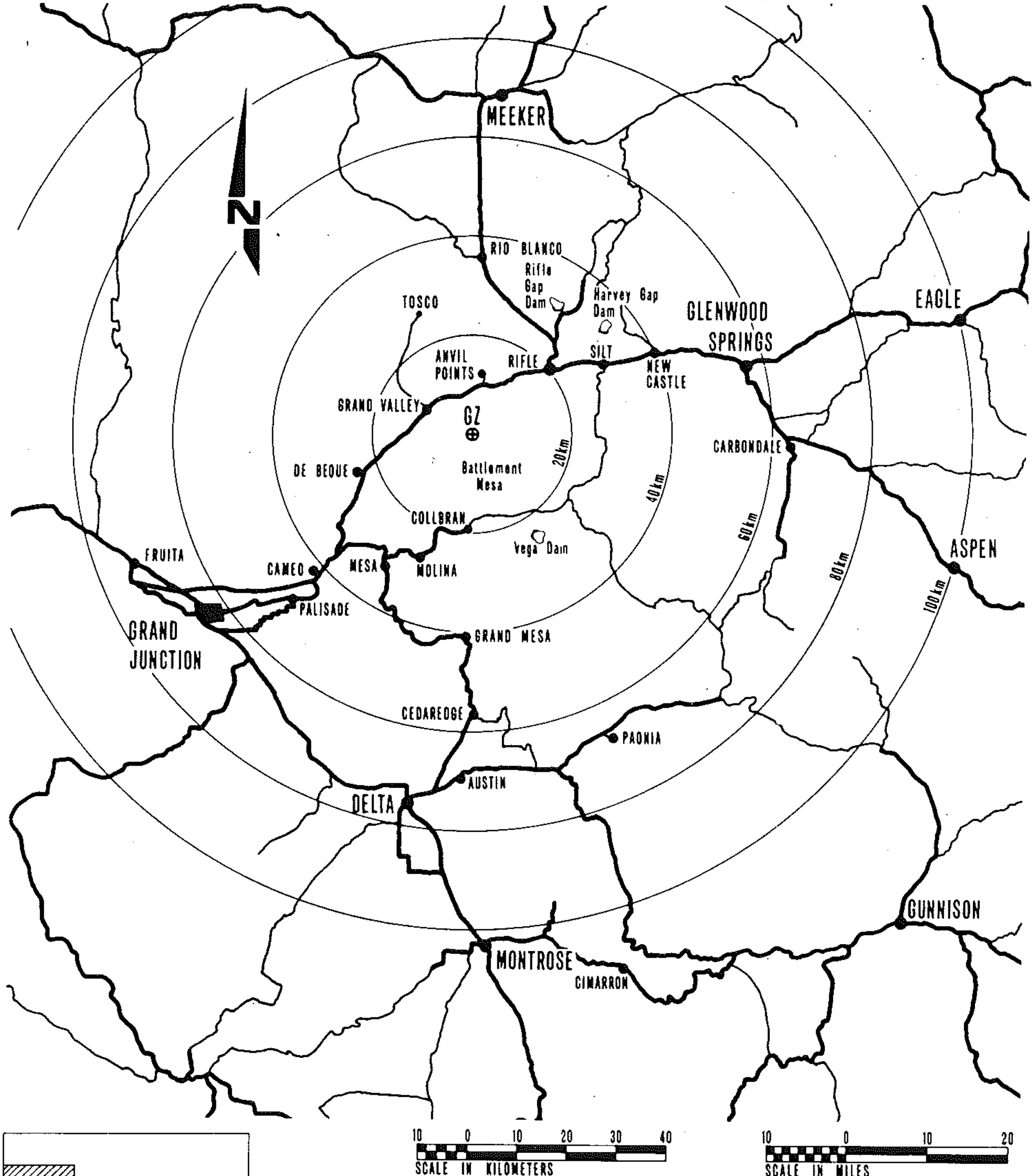
- ground motion data
- structure inventory data
- damage survey data

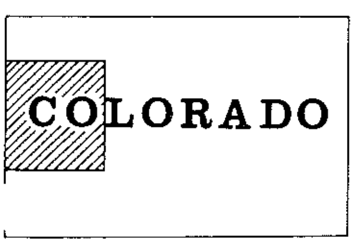
The specific data used in this study are discussed in this chapter.

There are approximately 2,500 low-rise residential and commercial buildings for which structure inventory and damage survey data are available from Project RULISON. The inventory includes towns and rural locations. Because of the limited number of seismometers available for the event, most of the ground motions obtained were recorded at towns in the area. Ground motion recordings obtained from rural locations were limited to a few close-in ranches. There are five towns in the area located at varying distances from Ground Zero (GZ) for which structure inventory, damage survey, and ground motion data are available: Collbran, DeBeque, Grand Valley, Rifle, and Silt. The combined structure population of these five towns (1,378 buildings) constitutes slightly more than half the total for the area inventoried and similarly includes slightly more than half the damage reported in the area. In consideration of these factors, the rural areas were excluded from this analysis. The locations of the above-mentioned five towns with respect to GZ are shown in Figure 1.

A. Ground Motion Data

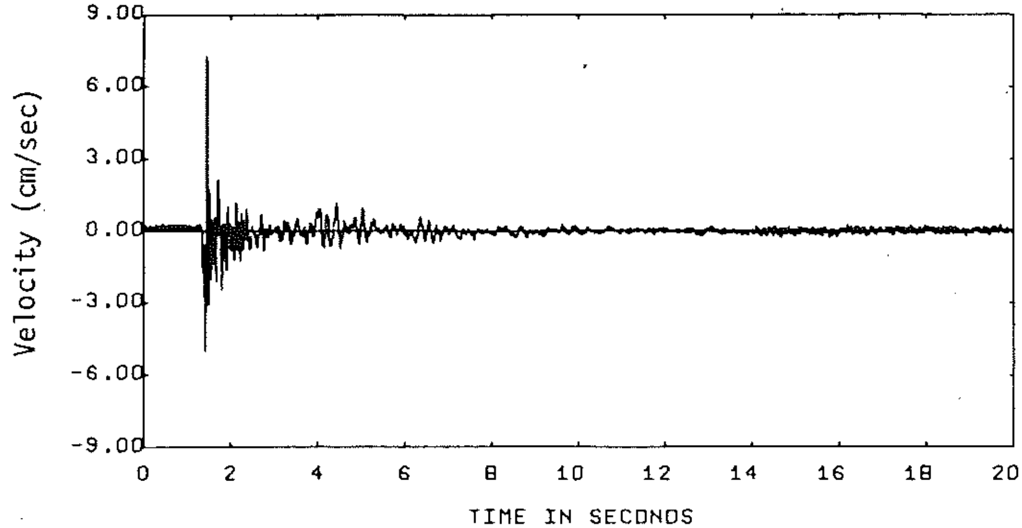
Several velocity records were obtained at various locations encompassing a fairly large geographical area around Ground Zero.[3] But, for the reasons stated above, only the records obtained in the above five towns are considered in this study. Figures 2 and 3 are samples of the velocity records obtained.



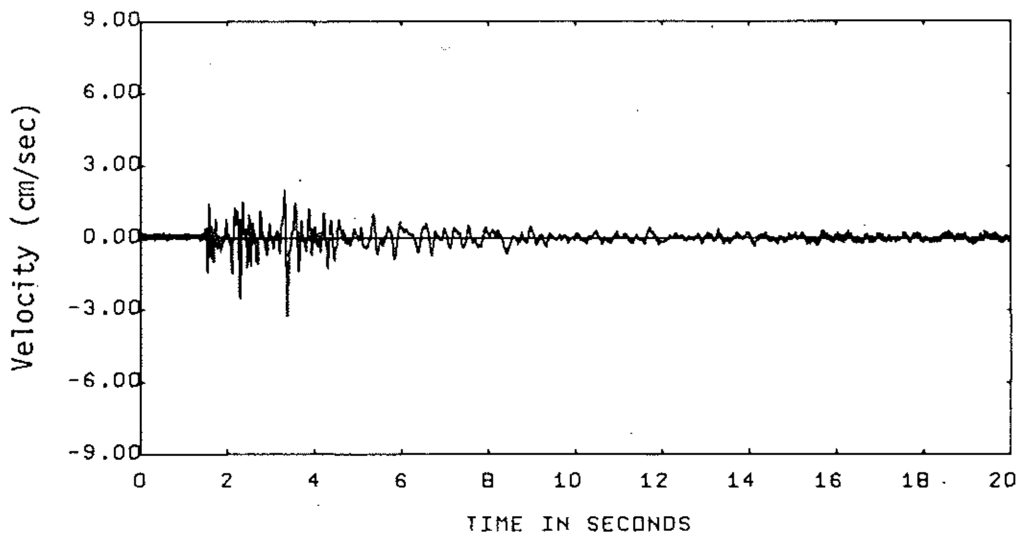


PROJECT RULISON
General Area Map

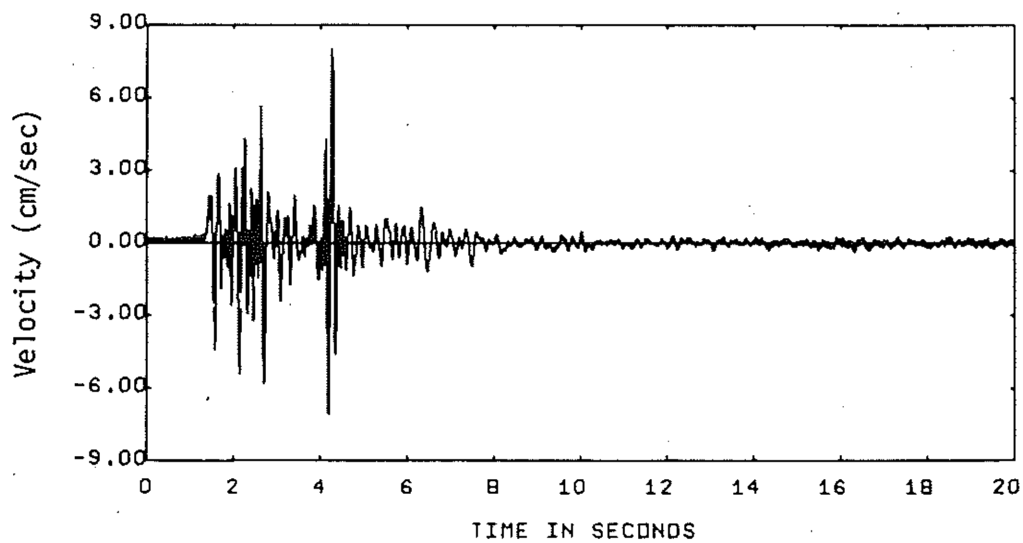
Figure 1



Vertical Component

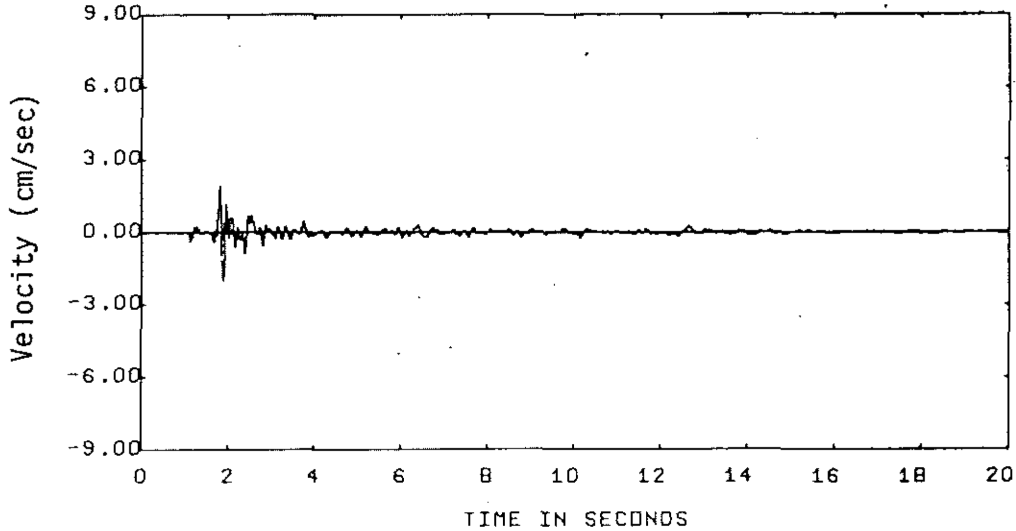


Tangential Component

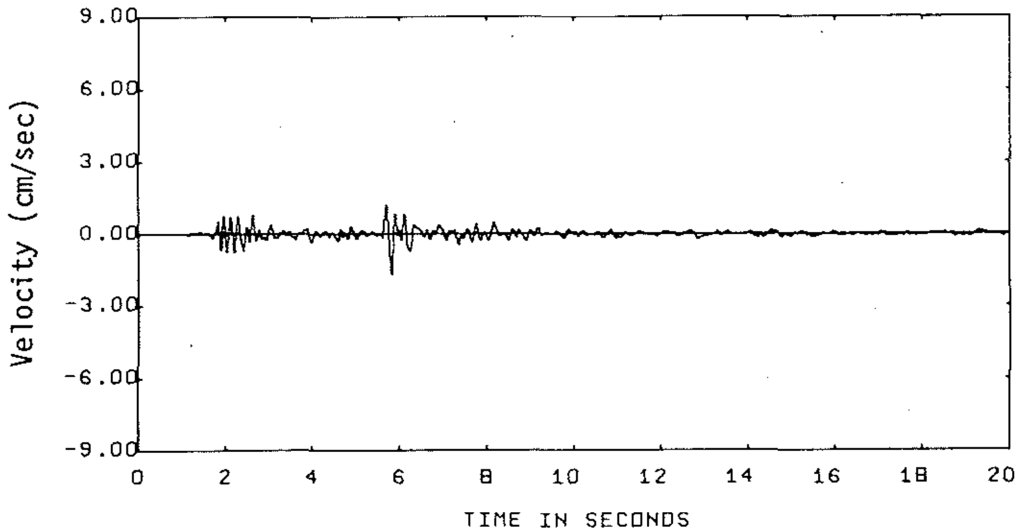


Radial Component

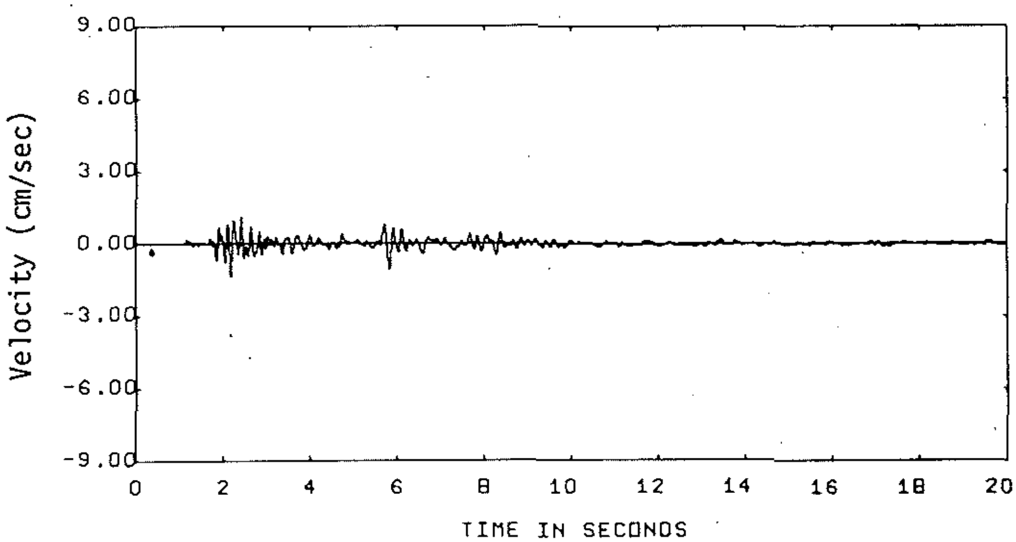
FIGURE 2 GROUND MOTION RECORDINGS
FOR THE RULISON UNE EVENT OF
SEPTEMBER 10, 1969: GRAND VALLEY STATION



Vertical Component



Tangential Component



Radial Component

FIGURE 3 GROUND MOTION RECORDINGS FOR THE RULISON UNE EVENT OF SEPTEMBER 10, 1969: DEBEQUE #1 STATION

The response spectrum curves,* Figures 4 through 9, and digitized ground motion records used in this study were obtained from Environmental Research Corporation (ERC). A general summary of observed ground motion for the RULISON event is included in the ERC report.[4]

B. Structure Data

The structure inventory of the five towns described was performed in view of this planned statistical research study. Therefore, it is probable that more detailed information was obtained than is necessary for damage prediction purposes. Nevertheless, even with this additional effort, detailed information such as chimney cross sections, construction materials of interior walls, etc., could not be collected because of time and budget limitations.

A sample of the structure inventory form used for the five towns is shown in Figure 10. All buildings (residential, commercial, and institutional) within the JAB-defined geographical limits for the five towns were inventoried. For residential locations, detached buildings such as garages and sheds were not counted as separate buildings. Trailer houses were excluded from this analysis because none were damaged.

C. Damage Data

For this study, the following definitions are used:

Complaint: any complaint made concerning property damage whether or not formalized as a claim (limited to types of damage listed on the following page)

Credible Damage: any of the above described complaints that was defined as credible by JAB, GAB (General Adjustment Bureau), or other investigators

*The ground motion measurement for the town of Collbran was incomplete in that only the first 3 seconds of motion were recorded. However, after examining and comparing all the records from the five towns, it was concluded that for the period range considered in this study the response spectra from these 3-second recordings were reasonably reliable.

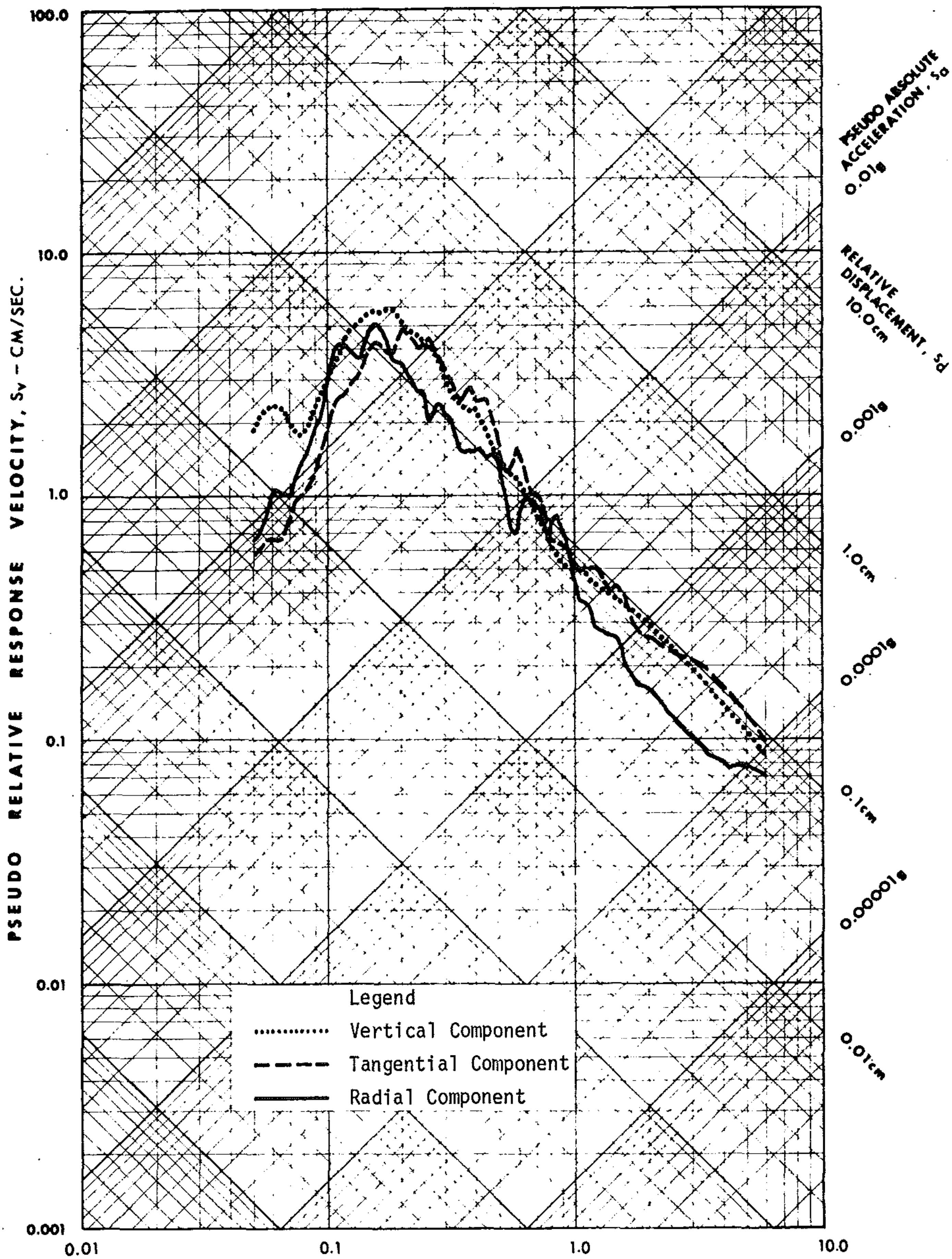


FIGURE 4 5% DAMPED RESPONSE SPECTRUM CURVES FOR THE RULISON UNE EVENT OF SEPTEMBER 10, 1969: DEBEQUE #1 STATION

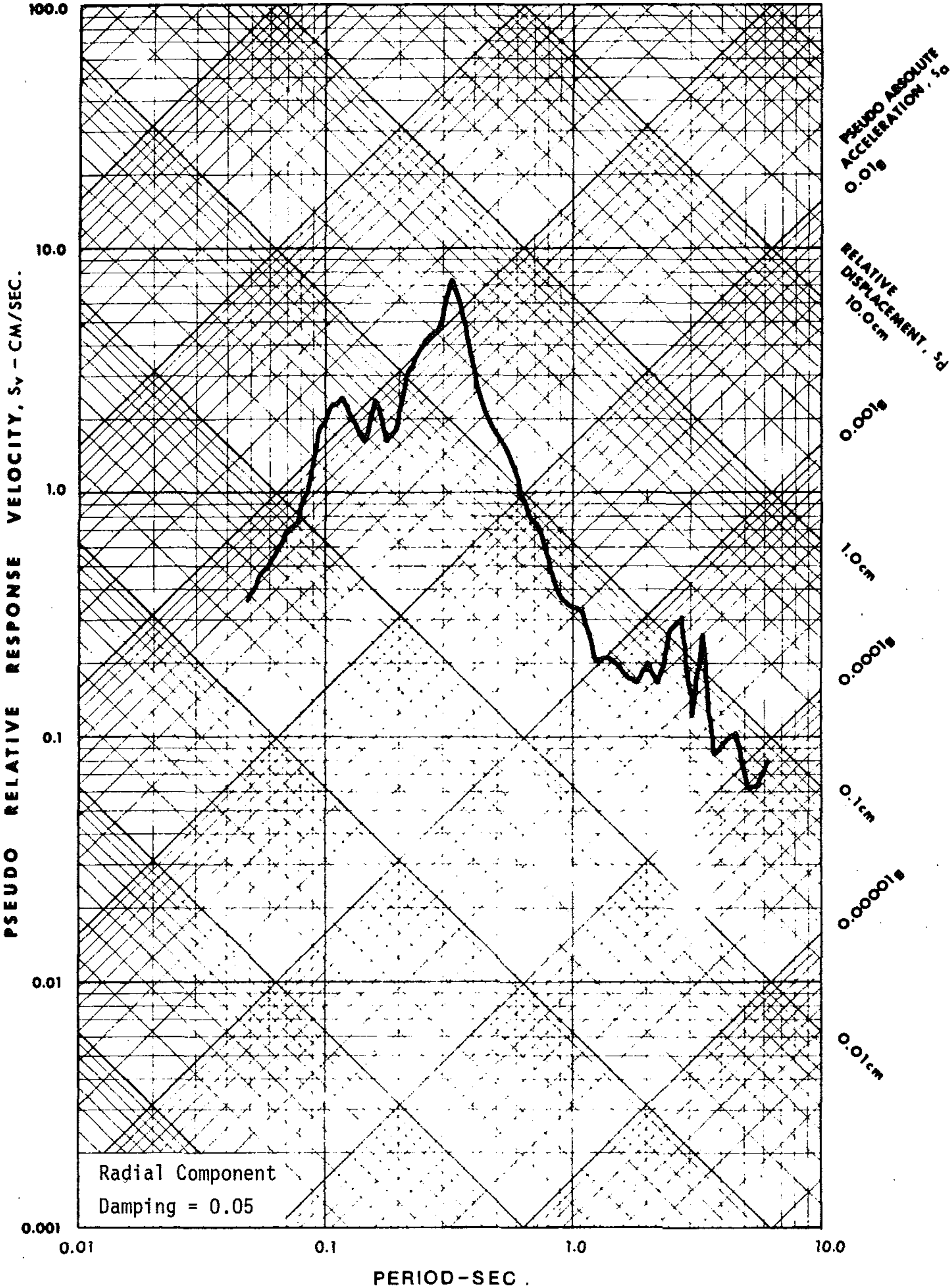


FIGURE 5 RESPONSE SPECTRA: RULISON Silt

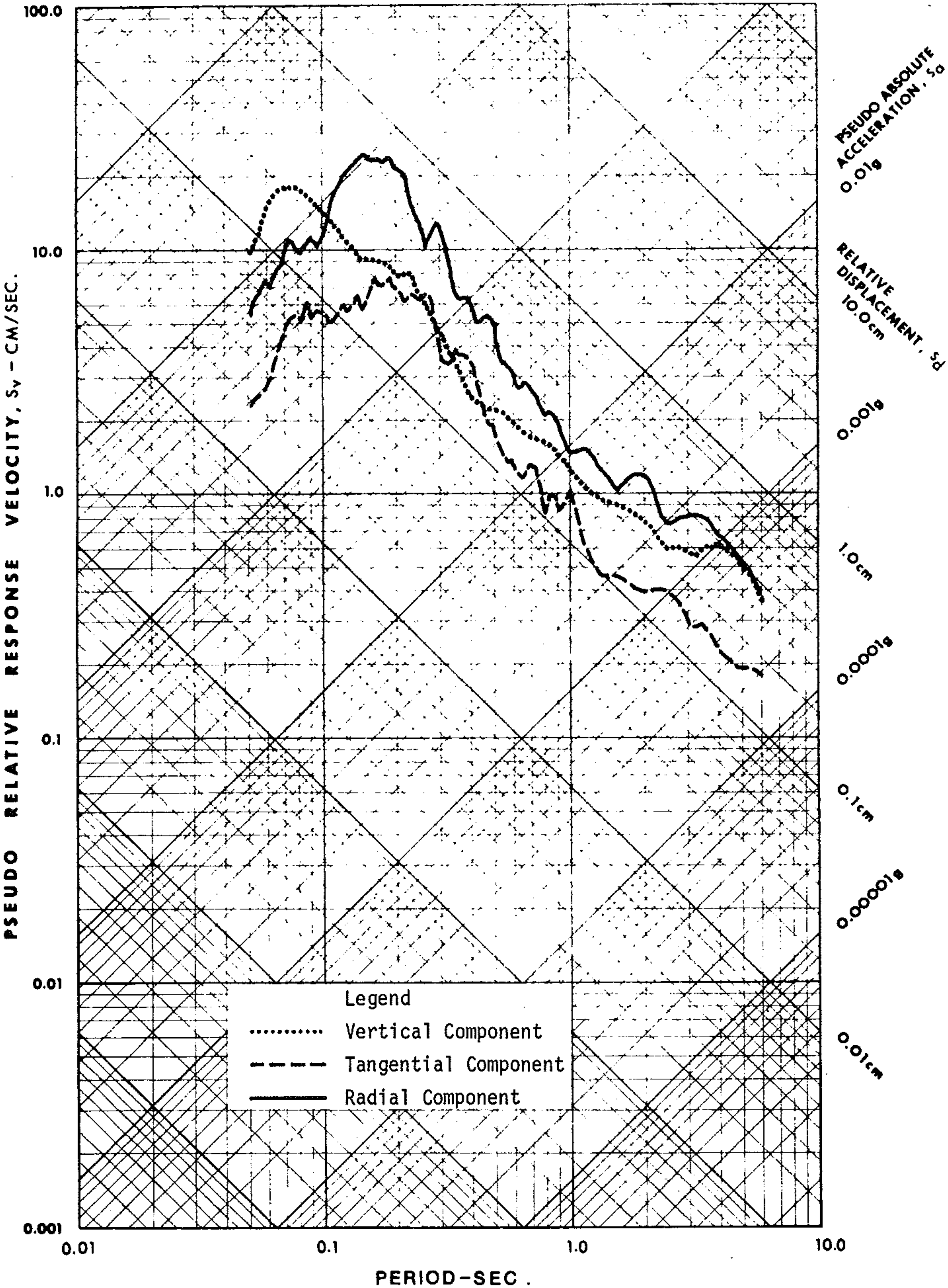


FIGURE 6 5% DAMPED RESPONSE SPECTRUM CURVES FOR THE RULISON UNE EVENT OF SEPTEMBER 10, 1969: GRAND VALLEY STATION

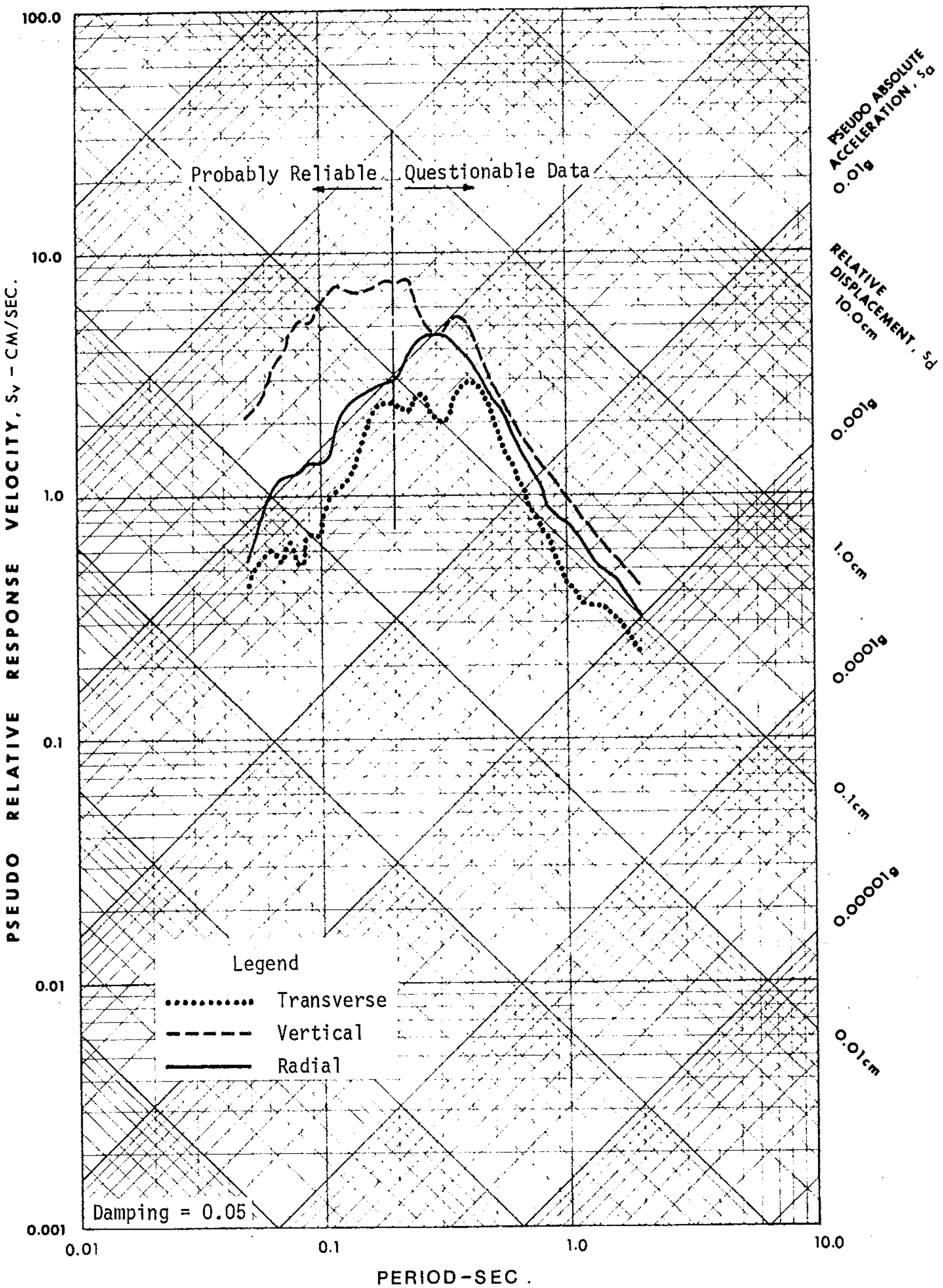


FIGURE 7 RESPONSE SPECTRA: RULISON Collbran

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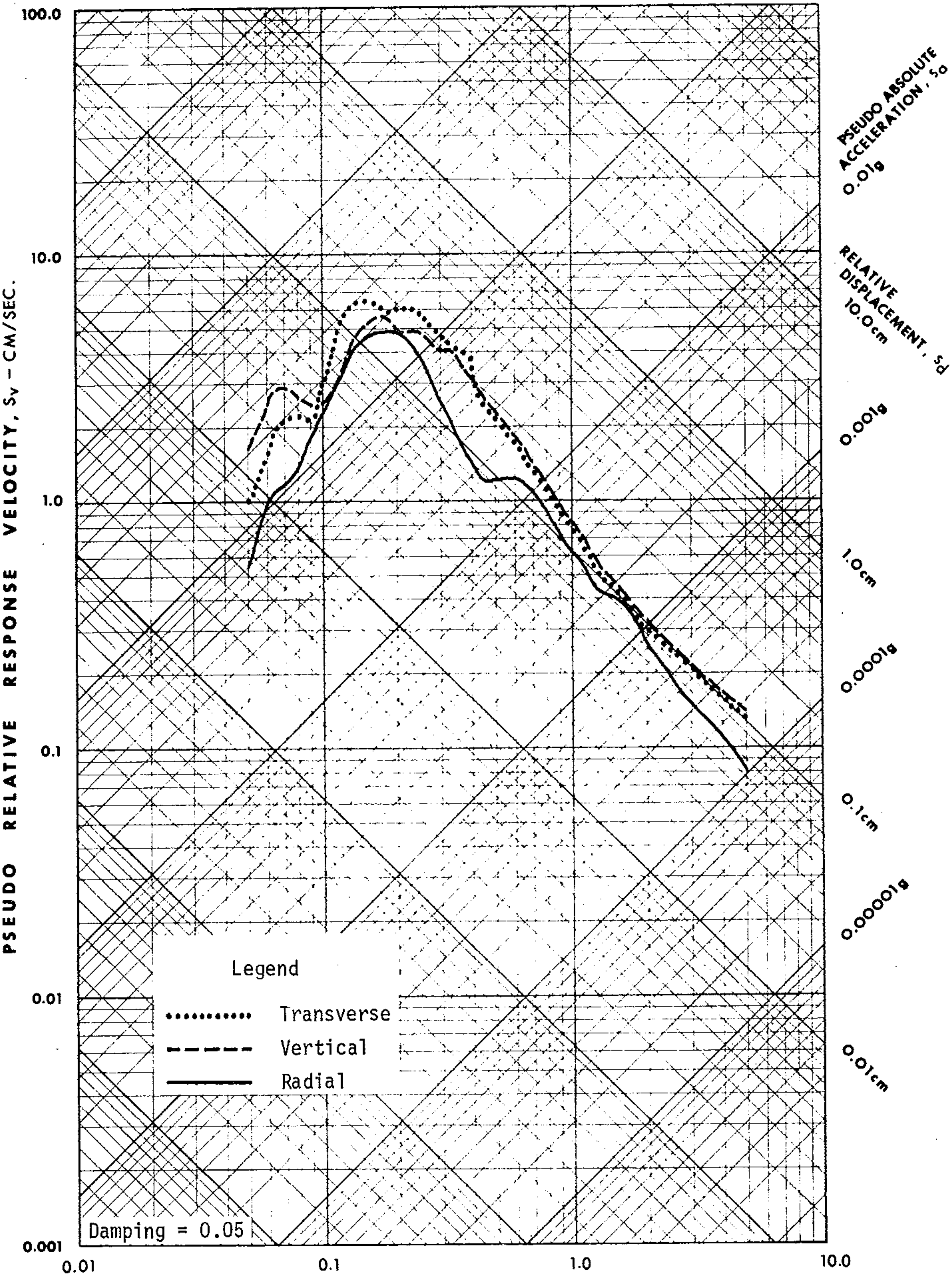

FIGURE 8 RESPONSE SPECTRA: RULISON Rifle Church

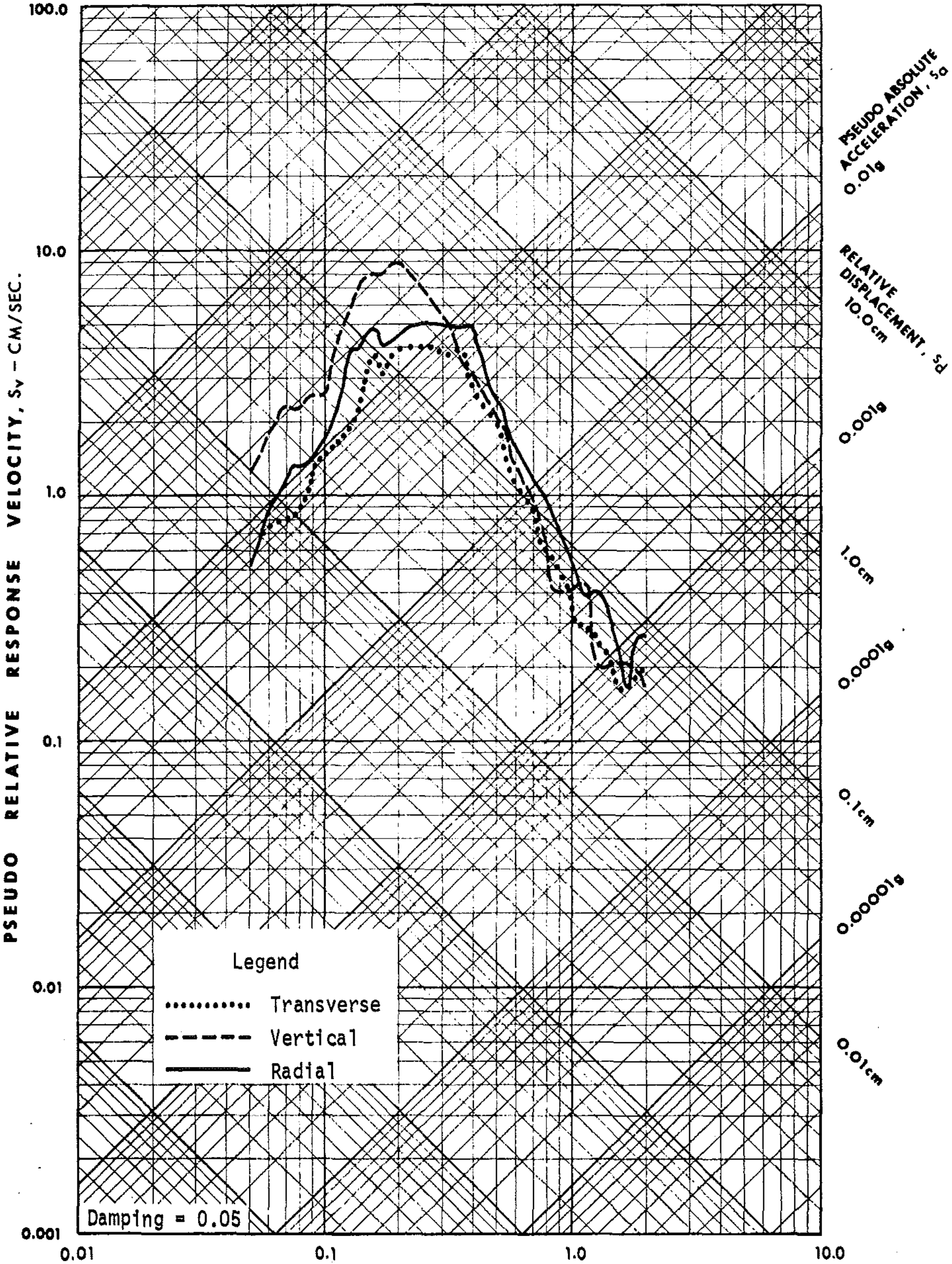

FIGURE 9 RESPONSE SPECTRA: RULISON Rifle Hill

Building Location Data

City: ______________________ Address: ______________________

Location No.: ______________________ Owner: ______________________

Building Classification Data

Occupancy:	☐ Residential	☐ Commercial	☐ Institutional
Frame Type:	☐ Wood	☐ Adobe	☐ Log
	☐ Masonry	☐ Metal	
Exterior Walls: (Siding)	☐ Wood	☐ Brick	☐ Concrete Block
	☐ Metal	☐ Cement Asbestos	☐ Adobe
	☐ Log	☐ Stone	☐ Other: ________

Building Height: (Stories) ☐ 1 ☐ 1-1/2 ☐ 2 ☐ 3 ☐ 4

Foundation Type: ☐ Wall Masonry Stone ☐ Mudsill ☐ Pier Masonry Timber

Chimney Type:	☐ Brick	☐ Stone	☐ Ceramic	☐ Metal Flue
	☐ Capped Brick	☐ Capped Stone	☐ Capped Ceramic	☐ None

Height of Chimney Above Roof (Feet) ______________________

Chimney Location ☐ Center (Ridge) ☐ End ☐ Eave

Building Age (yrs) ☐ 0-5 ☐ 5-10 ☐ 10-20 ☐ 20-40 ☐ Over 40

Building Classification No. ______________________

Building Value: Estimated $______________________ Assessed $______________________

Condition: ☐ Good ☐ Fair ☐ Poor

FIGURE 10 STRUCTURE INVENTORY FORM

In all there were 458 damage complaints filed for the RULISON event. Approximately half of this total (220) are included in this study. Most of the remaining complaints were received from the rural areas, but those in the five towns that were not related to buildings were also excluded. The types of complaints and credible damage included in this study are:

- chimneys (including fireplaces)
- interior walls
- exterior walls
- foundations
- windows
- others (building or household items)

A total of 326 claims filed for the RULISON event were acknowledged as credible damage; these involved damage to 165 buildings included in this study. The distribution of damage (by type) for the five towns included in this study is shown in Table 1.

D. Preprocessing of Data

The structure inventory data and damage data were programmed for computer processing. For each structure, both types of data were punched on a computer card. Figure 11 shows the format used for the arrangement of the information on a computer card.

TABLE 1

DISTRIBUTION OF DAMAGE BY TOWN AND TYPE

Town	Number of Buildings	Number of Buildings With Particular Credible Component Damage						
		Chimneys	Interior Walls	Masonry Walls	All Exterior Walls	Foundations	Windows	Other Building and Household Items
Collbran	139	0	3	1	1	2	0	1
DeBeque	105	1	5	1	1	1	0	0
Grand Valley	154	43	40	15	19	16	1	9
Rifle	812	21	46	11	15	21	4	4
Silt	168	1	2	1	2	0	0	0

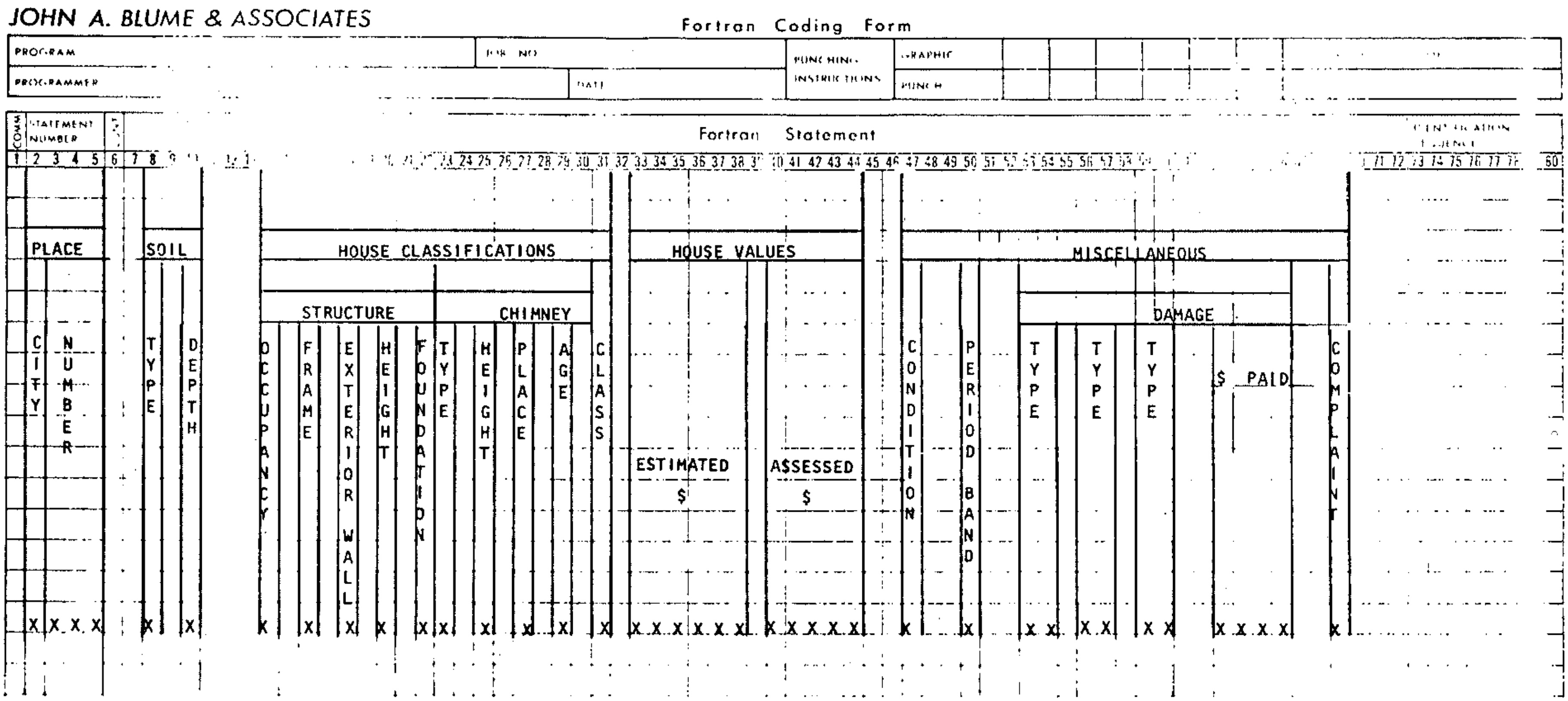

FIGURE 11 FORMAT OF COMPUTER CARD FOR STATISTICAL ANALYSIS

III. IDEALIZATIONS AND DEFINITIONS

Because of the complex nature of ground motion and of the causes and manifestations of structure damage, it is essential to generalize on the parameters pertinent to this type of study. This chapter provides descriptions of structure idealization, ground motion characterizations, and a definition of the damage ratio used in the correlation study.

A. Structure Idealization

In studying the damage to structures caused by ground motion, it is essential to consider the response of the structures. A structure's response is highly influenced by the proximity of its fundamental period to the dominant periods of ground motion. Observed data show that the fundamental periods of most one- and two-story structures fall in the range of 0.05 to 0.2 seconds. The particular period of a building is influenced by such parameters as:

- building materials
- frame type
- dimensions
- fenestration
- age
- condition
- soil conditions
- area of the interior and exterior wall

To obtain better insight concerning the manifestations of damage, the buildings were divided into two groups. Group 1 contains buildings with fundamental periods between 0.05 and 0.1 seconds (inclusive), and Group 2 contains structures with periods in the range of 0.1 to 0.2 seconds.

B. Ground Motion Characterizations

It has been previously shown[2] that the vector of the horizontal components of 5% damped response spectrum acceleration (S_{av}) effectively correlates ground motion with low-rise building damage. However, because no procedure has been developed for predicting S_{av}, it is not a convenient variable for damage prediction.

A convenient and applicable ground motion characterization for predicting damage to low-rise buildings is the envelope spectrum, defined by the envelope of the appropriate component response spectra. A comparison of envelope and vector for several earthquake and underground nuclear explosion ground motions showed that the horizontal component envelope acceleration response spectrum (S_{ae}) approximates S_{av} well in the period range of 0.05 to 0.2 seconds -- the fundamental period range of most low-rise buildings. Therefore S_{ae} values are used in this investigation to study the ground motion - damage relationships for building components.

The 5% damped response spectrum curves used in this study are shown in Figures 4 through 9. The values of 5% damped S_{ae} obtained by averaging the appropriate spectral curves over the appropriate period band for each group of buildings for the five towns are shown in Table 2.

C. Damage Ratio

To investigate the effects of various parameters on damage, it is essential to develop and utilize the concept of damage ratio. Damage ratio (DR) for buildings is defined by:

$$DR = \frac{\text{Number of Buildings Damaged}}{\text{Number of Buildings}}$$

TABLE 2

AVERAGE 5% DAMPED ACCELERATION RESPONSE SPECTRUM VALUES

Town	Envelope Pseudo Absolute Acceleration, S_{ae}, (g)		
	Group 1	Group 2	Average
Collbran	0.084	0.12	0.11
DeBeque	0.11	0.18	0.15
Grand Valley	0.77	0.93	0.88
Rifle	0.17	0.22	0.20
Silt	0.063*	0.092*	0.085*

* Approximated. Tangential component was questionable and therefore disregarded.

DR is quite general, and for a data sample it can be defined for various geographical areas, structure classes, and damaged components. This generalized damage ratio concept is utilized extensively in this study, and specific definitions of DR are given in the ground motion - damage correlations for the various damaged building components described in the next chapter.

IV. CORRELATION ANALYSIS AND RESULTS

Using the RULISON motion and damage data, the spectral values S_{ae} were correlated with damage ratios for the following building components:

- chimneys
- interior walls
- exterior walls
- foundations
- windows

The data were correlated using a linear regression analysis in the log domain, and the results are presented here in the form of plots. The correlation results and pertinent discussion are given in Sections A through E below.

A. Chimneys

The chimney damage ratio is defined as:

$$DR = \frac{\text{Number of Buildings with Damaged Chimneys}}{\text{Number of Buildings with Chimneys}}$$

Chimney damage ratios, considering factors that might influence damage, are given in Tables 3, 4, and 5.* The correlation of chimney damage ratio with spectral intensity values for the various groupings specified in these tables is discussed in Sections 2 through 5 below. Section 6 below gives a summary of the correlation for chimney damage.

1. General Considerations Concerning RULISON Chimney Damage

Chimneys have long been used in residential buildings, but effective guidelines for their design and construction were

---

*Since a unit perturbation in the sample size of the Collbran chimney data resulted in a change in damage ratio of more than 34%, these data were not considered in this study. This same criterion was used to exclude other data that caused similar statistical biasing effects.

TABLE 3

CHIMNEY DAMAGE RATIOS BY TOWN

Town	Chimney Damage Ratio (%)						
	Chimney Type		Building Group			Building Type	
	Brick	Stone	Group 1	Group 2	All Buildings with Chimneys	Masonry	Wood
DeBeque	1.5 $\left(\frac{1}{68}\right)$ †	* $\left(\frac{0}{1}\right)$	* $\left(\frac{0}{22}\right)$	2.1 $\left(\frac{1}{47}\right)$	1.5 $\left(\frac{1}{69}\right)$	* $\left(\frac{0}{13}\right)$	1.8 $\left(\frac{1}{56}\right)$
Grand Valley	41.9 $\left(\frac{39}{93}\right)$	57.1 $\left(\frac{4}{7}\right)$	45.1 $\left(\frac{23}{51}\right)$	40.8 $\left(\frac{20}{49}\right)$	43.0 $\left(\frac{43}{100}\right)$	42.9 $\left(\frac{6}{14}\right)$	43.0 $\left(\frac{37}{86}\right)$
Rifle	4.4 $\left(\frac{19}{433}\right)$	12.5 $\left(\frac{2}{16}\right)$	4.2 $\left(\frac{11}{264}\right)$	5.4 $\left(\frac{10}{186}\right)$	4.7 $\left(\frac{21}{450}\right)$	8.3 $\left(\frac{10}{121}\right)$	3.3 $\left(\frac{11}{329}\right)$
Silt	0.9 $\left(\frac{1}{114}\right)$	* $\left(\frac{0}{2}\right)$	* $\left(\frac{0}{33}\right)$	1.2 $\left(\frac{1}{83}\right)$	0.9 $\left(\frac{1}{116}\right)$	* $\left(\frac{0}{23}\right)$	1.1 $\left(\frac{1}{93}\right)$

* Not included in regression analysis.

† Ratios expressed as fractions indicate sample sizes: number of damaged chimneys over number of chimneys. Note that because some structure inventory sheets were incomplete, the sum of the numerators or denominators of one pair of columns will not necessarily equal the sum of the numerators or denominators of the other pairs of columns.

TABLE 4

DAMAGE RATIOS FOR CAPPED AND UNCAPPED CHIMNEYS

Town	Chimney Damage Ratio, DR, (%)		$\frac{\text{DR (uncapped)}}{\text{DR (capped)}}$
	Capped Brick	Uncapped Brick	
Grand Valley	41.7 $\left(\frac{20}{48}\right)^{\dagger}$	42.2 $\left(\frac{19}{45}\right)$	1.0
Rifle	3.8 $\left(\frac{12}{316}\right)$	6.0 $\left(\frac{7}{117}\right)$	1.6

† Ratios expressed as fractions indicate sample sizes: number of damaged chimneys over number of chimneys

TABLE 5

CHIMNEY DAMAGE RATIOS BY CHIMNEY HEIGHT

Chimney Height Above Roof Line (ft)	Chimney Damage Ratio (%)					
	Grand Valley			Rifle		
	Group 1	Group 2	Average	Group 1	Group 2	Average
3, 4, and 5	33.3 $\left(\frac{12}{36}\right)$ †	24.3 $\left(\frac{9}{37}\right)$	28.8 $\left(\frac{21}{73}\right)$	2.6 $\left(\frac{5}{193}\right)$	3.8 $\left(\frac{5}{130}\right)$	3.1 $\left(\frac{10}{323}\right)$
6 and 7	* $\left(\frac{0}{0}\right)$	25.0 $\left(\frac{1}{4}\right)$	25.0 $\left(\frac{1}{4}\right)$	3.1 $\left(\frac{1}{32}\right)$	10.7 $\left(\frac{3}{28}\right)$	6.7 $\left(\frac{4}{60}\right)$
Over 7	66.7 $\left(\frac{2}{3}\right)$	* $\left(\frac{0}{0}\right)$	66.7 $\left(\frac{2}{3}\right)$	12.5 $\left(\frac{3}{24}\right)$	15.4 $\left(\frac{2}{13}\right)$	10.8 $\left(\frac{4}{37}\right)$

* Not included in regression analysis

† Ratios expressed as fractions indicate sample sizes: number of damaged chimneys over number of chimneys

established only during this century. Experience has shown that a chimney is one of the most hazardous components of a residential building and must be properly designed to withstand lateral loads. After the seismic risk map was established (1927), along with other recommendations for earthquake resistant design of buildings, some guidelines for the construction of chimneys were also established. The current Uniform Building Code[5] recommends that chimneys in wood-frame buildings in moderate and severe seismic activity zones (Zone 2 and Zone 3) be reinforced and anchored laterally to the building at specific points.

Colorado is in a region of relatively low seismic activity (Zone 1). Therefore neither anchorage nor reinforcement has been required for chimneys in residential buildings in the RULISON area, and it is most likely that few chimneys were constructed with these strengthening measures. This fact must be considered in any attempt to apply the RULISON chimney motion-damage results, given below, to another geographical area.

2. Chimney Type

The vast majority of chimneys in the RULISON area were constructed of stone or brick, and therefore these are the only types considered in this study. Table 3 shows the damage ratios for stone and brick chimneys for the selected towns, and plots of these damage ratios versus the spectral intensity S_{ae} are given in Figure 12. Damage ratios equal to zero were not used in the regression analysis, but -- where practical -- an estimate of their upper bounds was made using the assumption that if one more data sample had been included in the test, one failure would have occurred. That is,

$$DR = \frac{x + 1}{n + 1} \quad .$$

For x = 0,

$$DR = \frac{1}{n + 1}$$

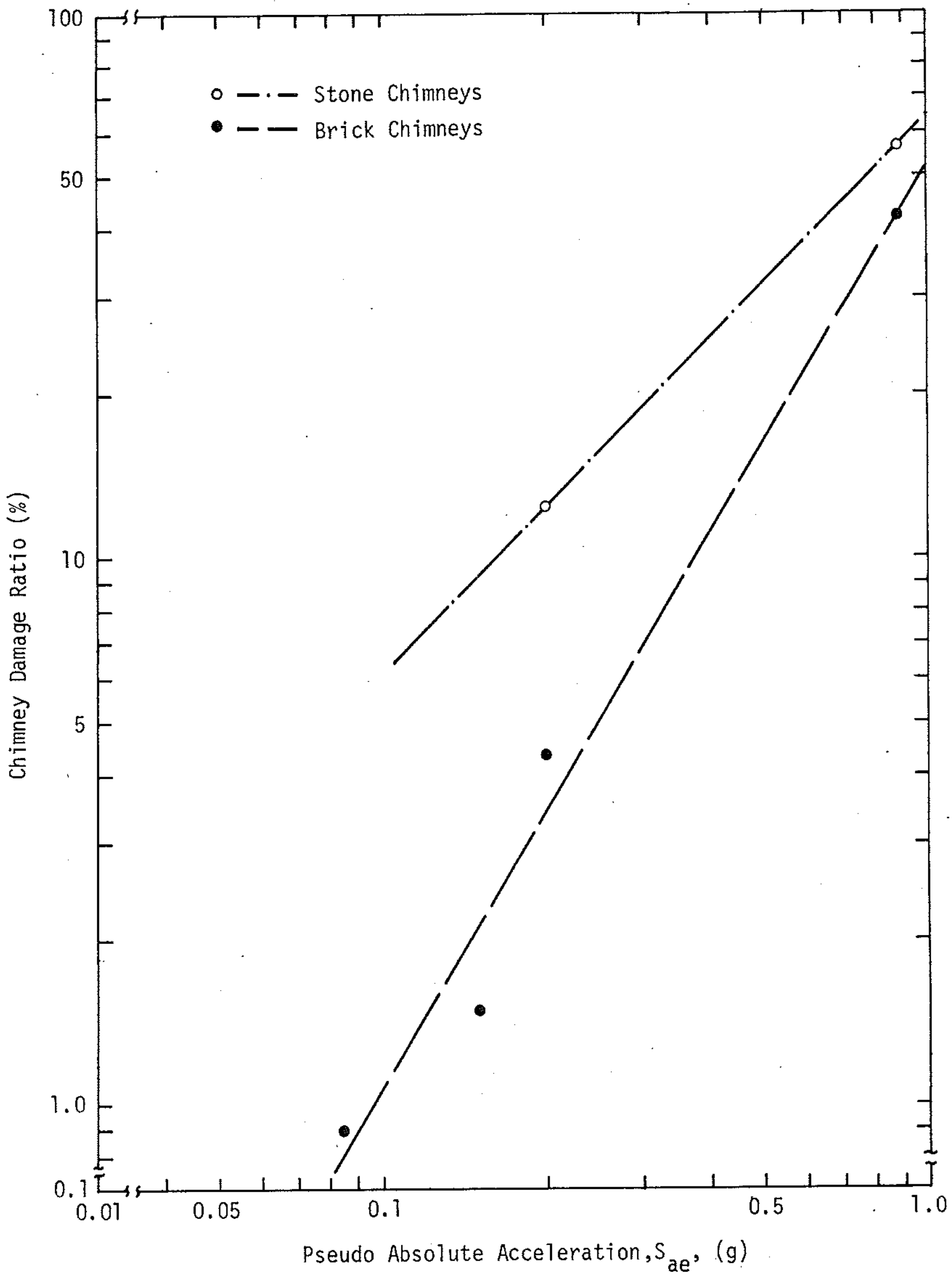

FIGURE 12 CHIMNEY DAMAGE RATIO (BY CHIMNEY TYPE) VS SPECTRAL INTENSITY

Where appropriate, these upper bound estimates are shown with square symbols in the figures.

Because there are only two data points for stone chimneys, the line drawn through them is not reliable for quantitative analysis, but the data are useful for qualitative comparison. The figure indicates that stone chimneys have a lower damage threshold* than brick chimneys. This observation is consistent with that of a similar study[6] conducted correlating residential building damage with ground motion resulting from the San Fernando, California, earthquake of February 9, 1971.

3. *Building Group and Building Type*

Damage ratios for the two building groups and for the two building types (wood-frame and masonry) are given in Table 3. Plots of these damage ratios versus spectral intensity are given in Figures 13 and 14.

Although the number of data points for Group 1 and masonry buildings is inadequate for quantitative evaluation, the data are useful for qualitative comparison. Figure 13 shows that for low spectral intensity, chimneys in masonry buildings have lower damage thresholds than chimneys in wood-frame buildings, but that as spectral intensity increases, the difference in damage ratio decreases. Figure 14 does not indicate a substantial difference in the motion-damage relationships for chimneys in Group 1 and Group 2 buildings.

4. Chimney Condition

Because the lateral force carrying capacity of a chimney is so highly dependent upon mortar strength, the condition of

*In this investigation, an object with a low damage threshold is defined as one that is damaged at low spectral motion intensities.

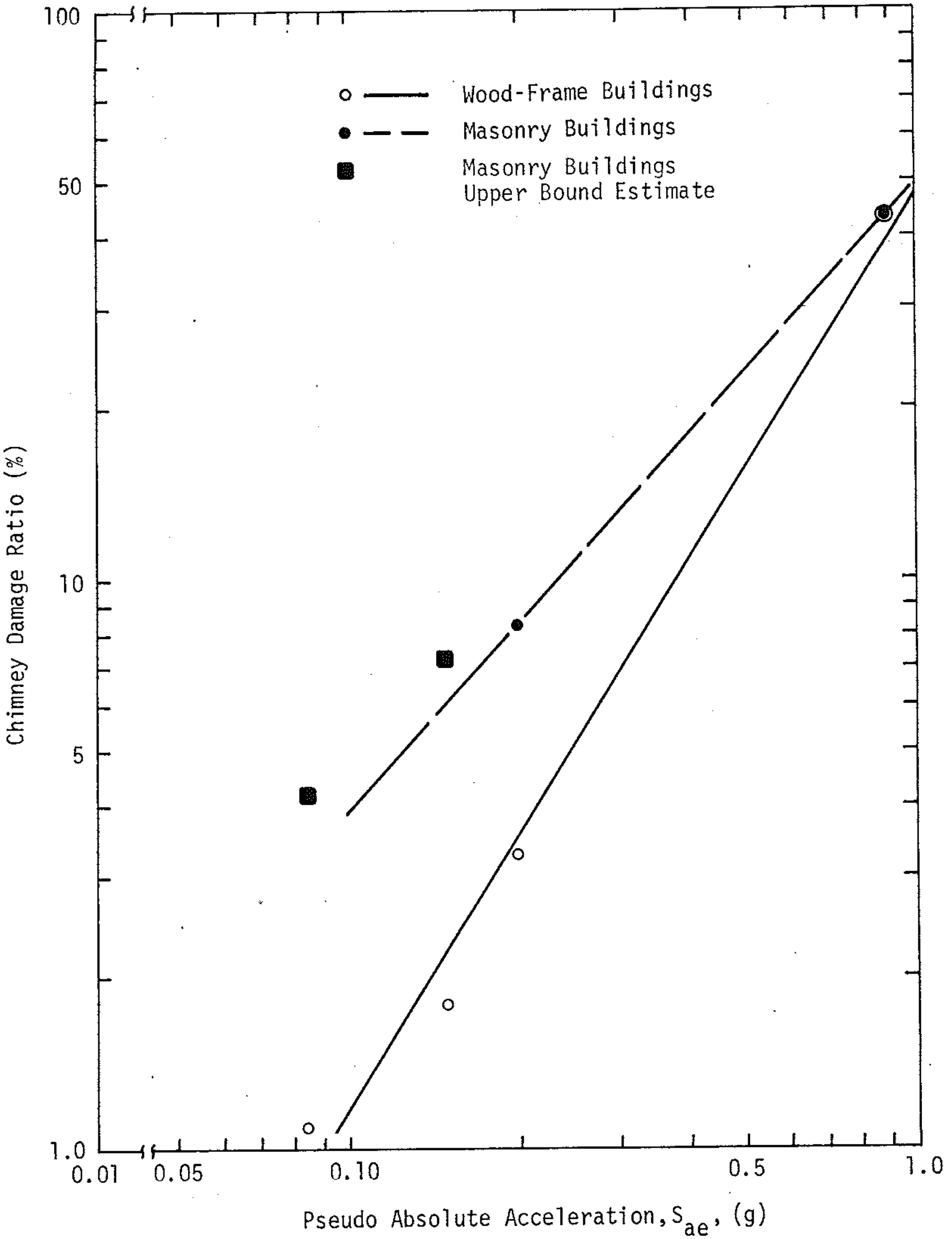

FIGURE 13 CHIMNEY DAMAGE RATIO (BY BUILDING TYPE) VS SPECTRAL INTENSITY

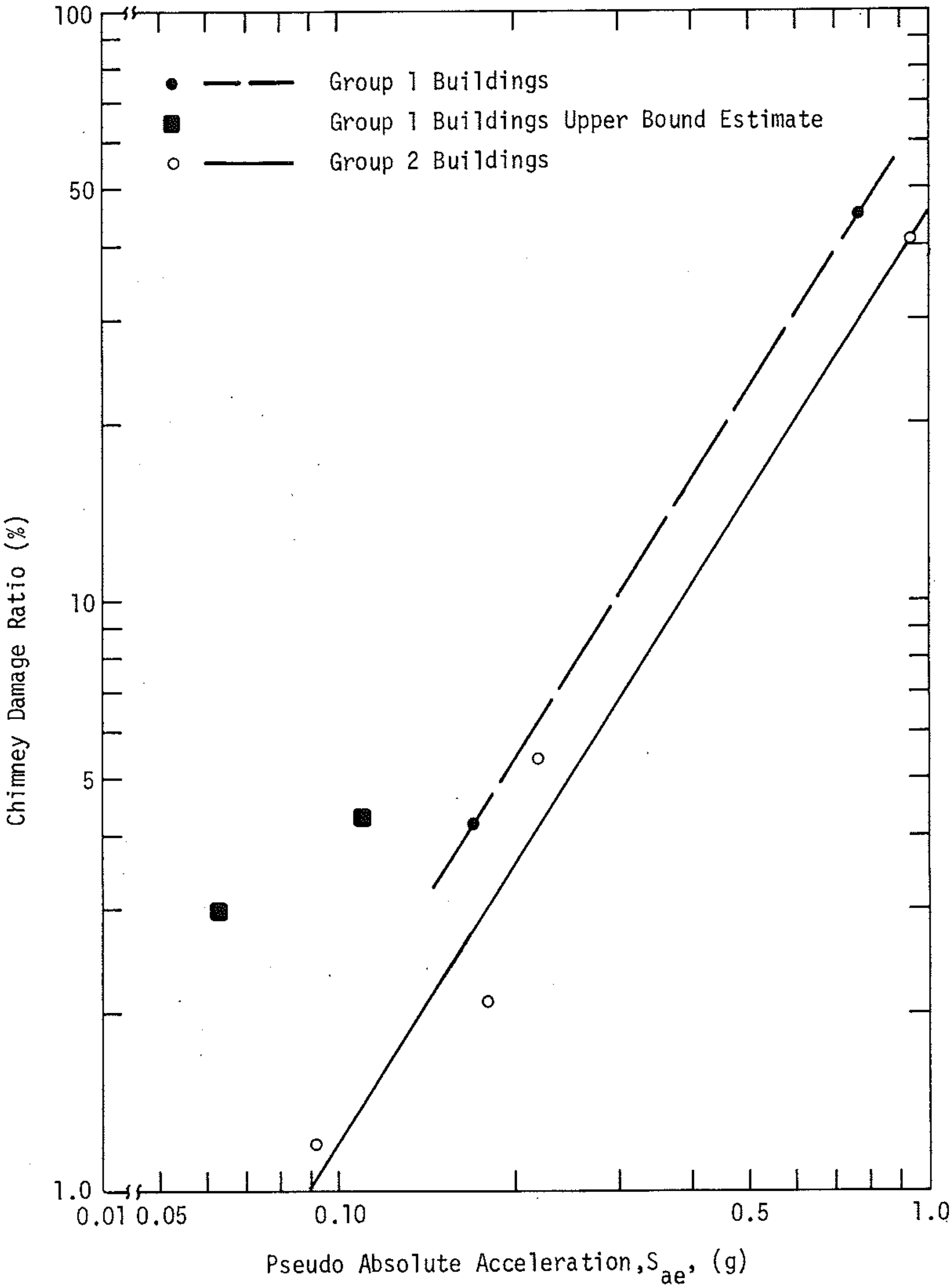

FIGURE 14 CHIMNEY DAMAGE RATIO (BY BUILDING GROUP) VS SPECTRAL INTENSITY

the mortar has a significant influence on a chimney's susceptibility to damage. Weathering is one of the main causes of mortar deterioration, and capped chimneys are generally less susceptible to weathering than uncapped chimneys. Therefore, damage ratios for uncapped chimneys may be expected to be higher than damage ratios for capped chimneys.

Table 4 presents damage ratios for capped brick and uncapped brick chimneys as well as the ratio of the damage ratios of uncapped over capped chimneys. These results show that for lower spectral motion intensity, uncapped chimneys are more readily damaged but that for higher motion intensity, capped chimneys are not significantly more damage resistant than uncapped chimneys.

5. <u>Chimney Height</u>

Damage ratio is certainly a function of chimney height. Chimneys that terminate near the roof line of a structure are less susceptible to damage than those that extend high above the roof line.

Table 5 summarizes chimney damage ratios according to chimney height. The results show that the damage ratio generally increases as the chimney height above the roof line increases. This general trend is true for both low and high spectral motion intensities.

6. <u>Overall Chimney Motion - Damage Relationship</u>

The variation of damage ratio for all chimneys with spectral motion intensity S_{ae} is shown in Figure 15. The figure shows that approximately 1% of the chimneys subjected to a spectral acceleration intensity $S_{ae} \simeq 0.1g$ will be damaged. Similarly, for a spectral acceleration intensity $S_{ae} \simeq 1.0g$, more than 50% of the chimneys are expected to be damaged.

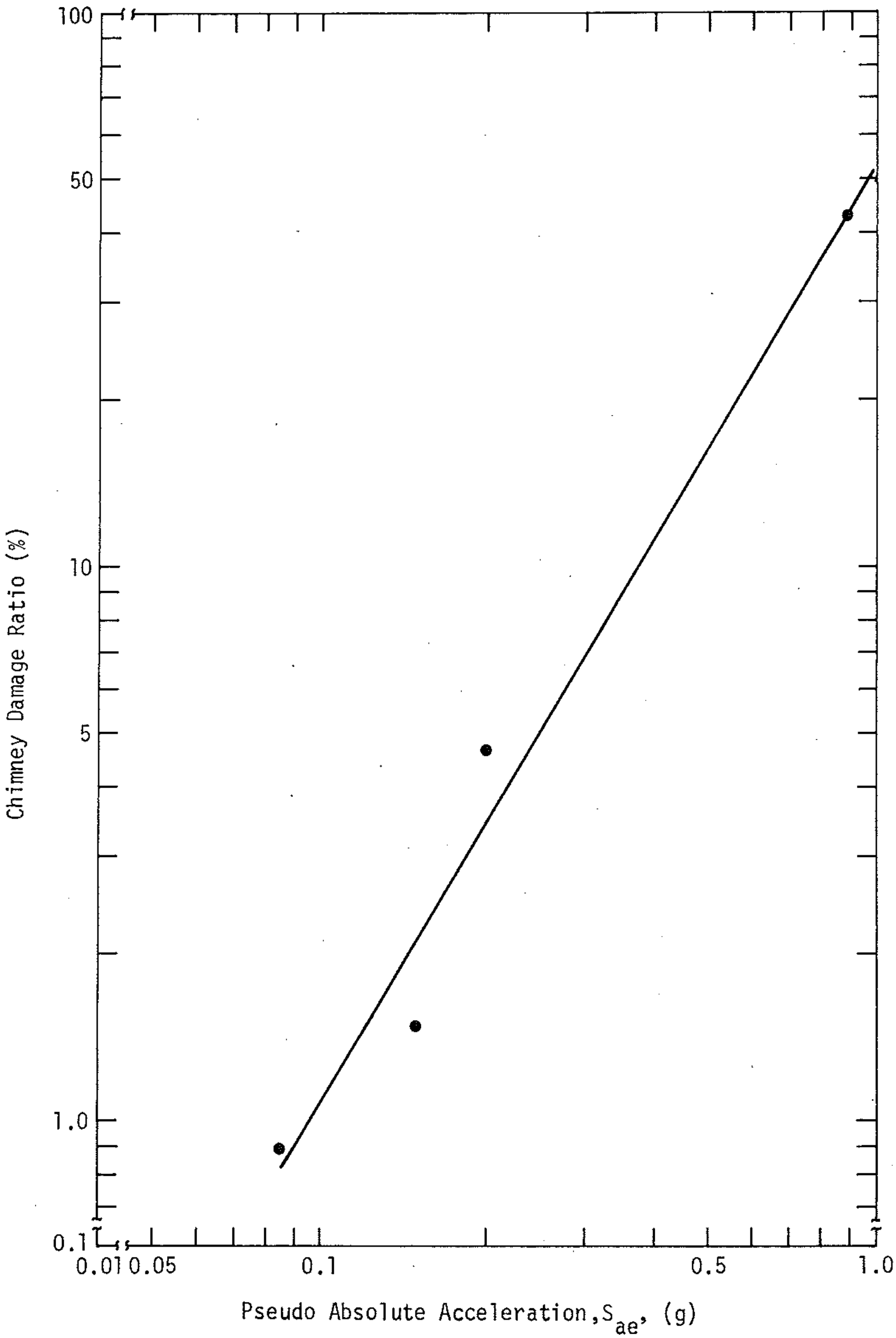

FIGURE 15 CHIMNEY DAMAGE RATIO (FOR ALL BUILDINGS WITH CHIMNEYS) VS SPECTRAL INTENSITY

B. Interior Walls

The damage ratio for interior walls is defined as:

$$DR_i = \frac{\text{Number of Buildings with Damaged Interior Walls}}{\text{Number of Buildings}}$$

Table 6 presents the damage ratios of interior walls for the various building groups in the five towns. The plots of damage ratio for walls in masonry and wood-frame buildings (Figure 16) indicate that interior walls in masonry buildings are more susceptible to damage than interior walls in wood-frame buildings, although the difference decreases as the spectral intensity increases. Figure 17 shows the variation of damage ratio of interior walls for the two building groups with spectral intensity S_{ae}. These two figures suggest that the interior walls of the masonry buildings and Group 2 buildings have the lowest and the highest damage thresholds, respectively.

C. Exterior Walls

In the RULISON area nearly all exterior walls are of masonry or wood-frame construction. Investigation of the ground motion - exterior wall damage relationship is necessary because of the important role of exterior walls in the dynamic response and safety of buildings.

The damage ratio for exterior walls is defined as:

$$DR_e = \frac{\begin{array}{c}\text{Number of Buildings with Damaged}\\ \text{Exterior Walls of a Particular Type}\end{array}}{\begin{array}{c}\text{Number of Buildings with Exterior}\\ \text{Walls of a Particular Type}\end{array}}$$

Figure 18 shows the increase of masonry wall damage with increase of spectral intensity. It indicates that masonry walls are highly susceptible to damage and that at a high spectral intensity, S_{ae} = 1g, more than 50% of masonry walls may be damaged. The second line in Figure 18 was plotted considering all damaged exterior walls, irrespective of type. Comparing the two lines, it

TABLE 6

INTERIOR WALL DAMAGE RATIOS BY BUILDING GROUP

Town	Interior Wall Damage Ratio (%)		
	Group 1	Group 2	All Buildings
Collbran	2.7 $\left(\frac{1}{37}\right)^{\dagger}$	2.0 $\left(\frac{2}{102}\right)$	2.2 $\left(\frac{3}{139}\right)$
DeBeque	5.1 $\left(\frac{2}{39}\right)$	4.5 $\left(\frac{3}{66}\right)$	4.8 $\left(\frac{5}{105}\right)$
Grand Valley	30.5 $\left(\frac{25}{82}\right)$	20.8 $\left(\frac{15}{72}\right)$	26.0 $\left(\frac{40}{154}\right)$
Rifle	5.0 $\left(\frac{27}{539}\right)$	7.0 $\left(\frac{19}{273}\right)$	5.7 $\left(\frac{46}{812}\right)$
Silt	1.8 $\left(\frac{1}{57}\right)$	0.9 $\left(\frac{1}{111}\right)$	1.2 $\left(\frac{2}{168}\right)$

† Ratios expressed as fractions indicate sample size: number of damaged interior walls over number of buildings

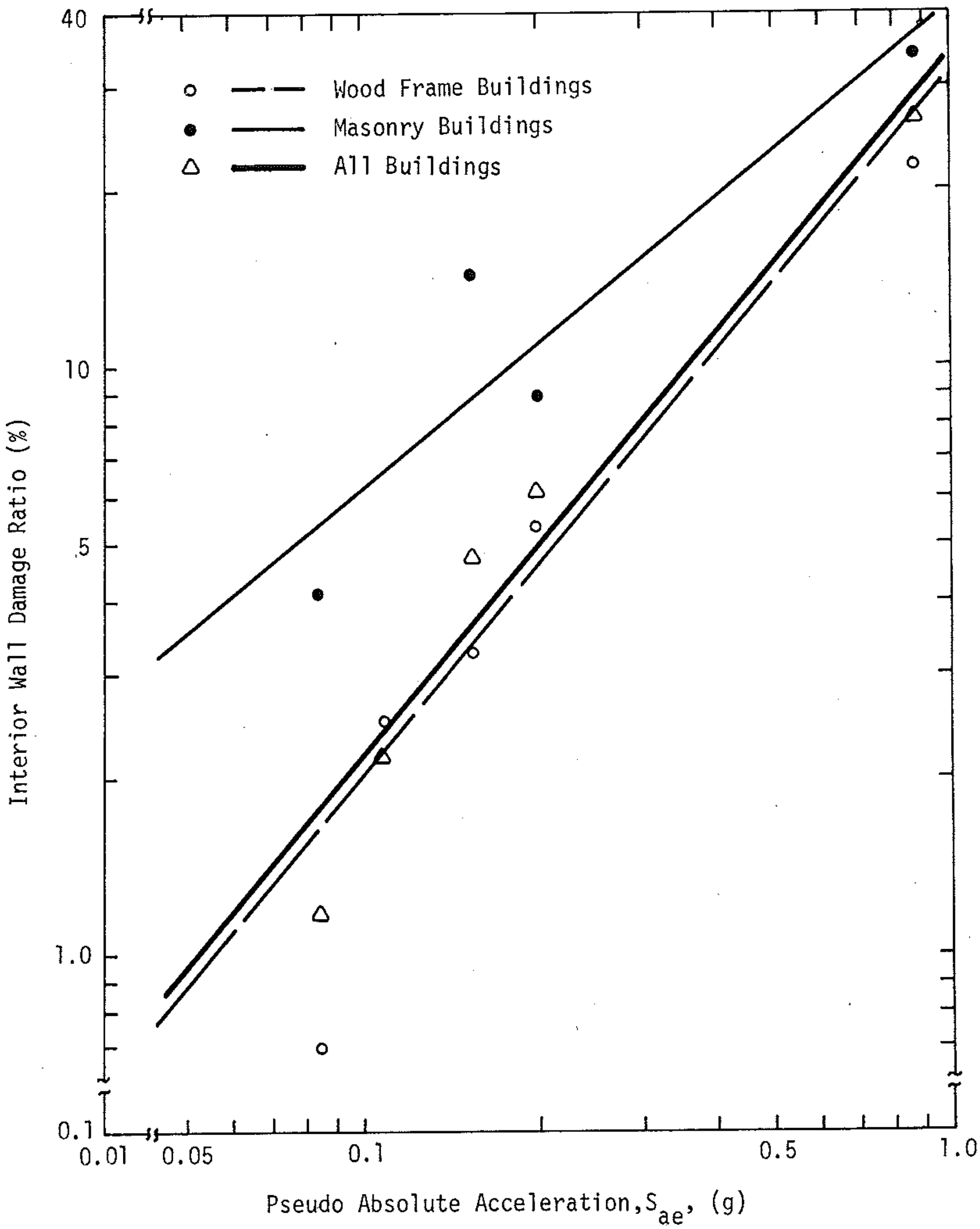

FIGURE 16 DAMAGE RATIO FOR INTERIOR WALLS (BY BUILDING TYPE) VS SPECTRAL INTENSITY

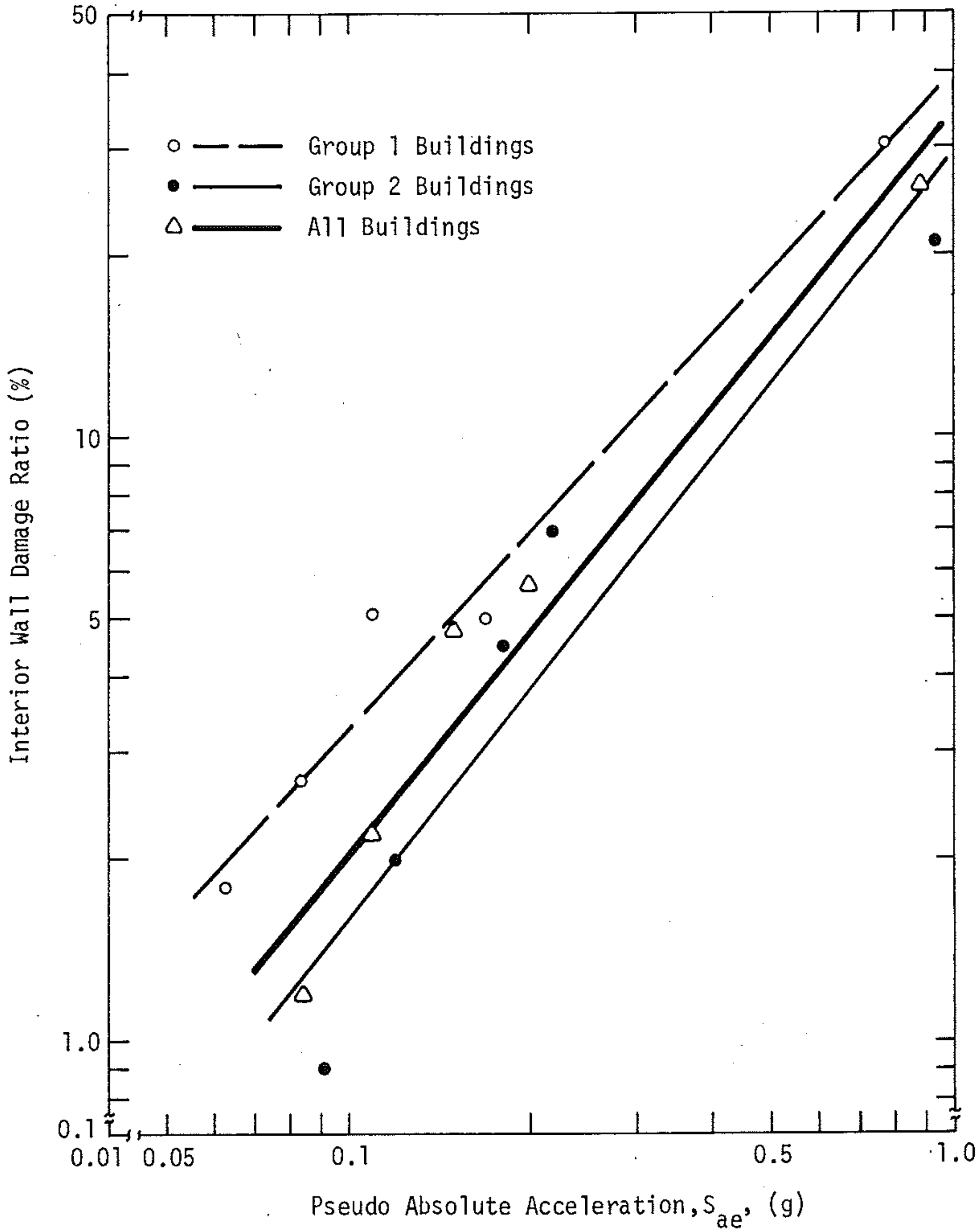

FIGURE 17 DAMAGE RATIO FOR INTERIOR WALLS (BY BUILDING GROUP) VS SPECTRAL INTENSITY

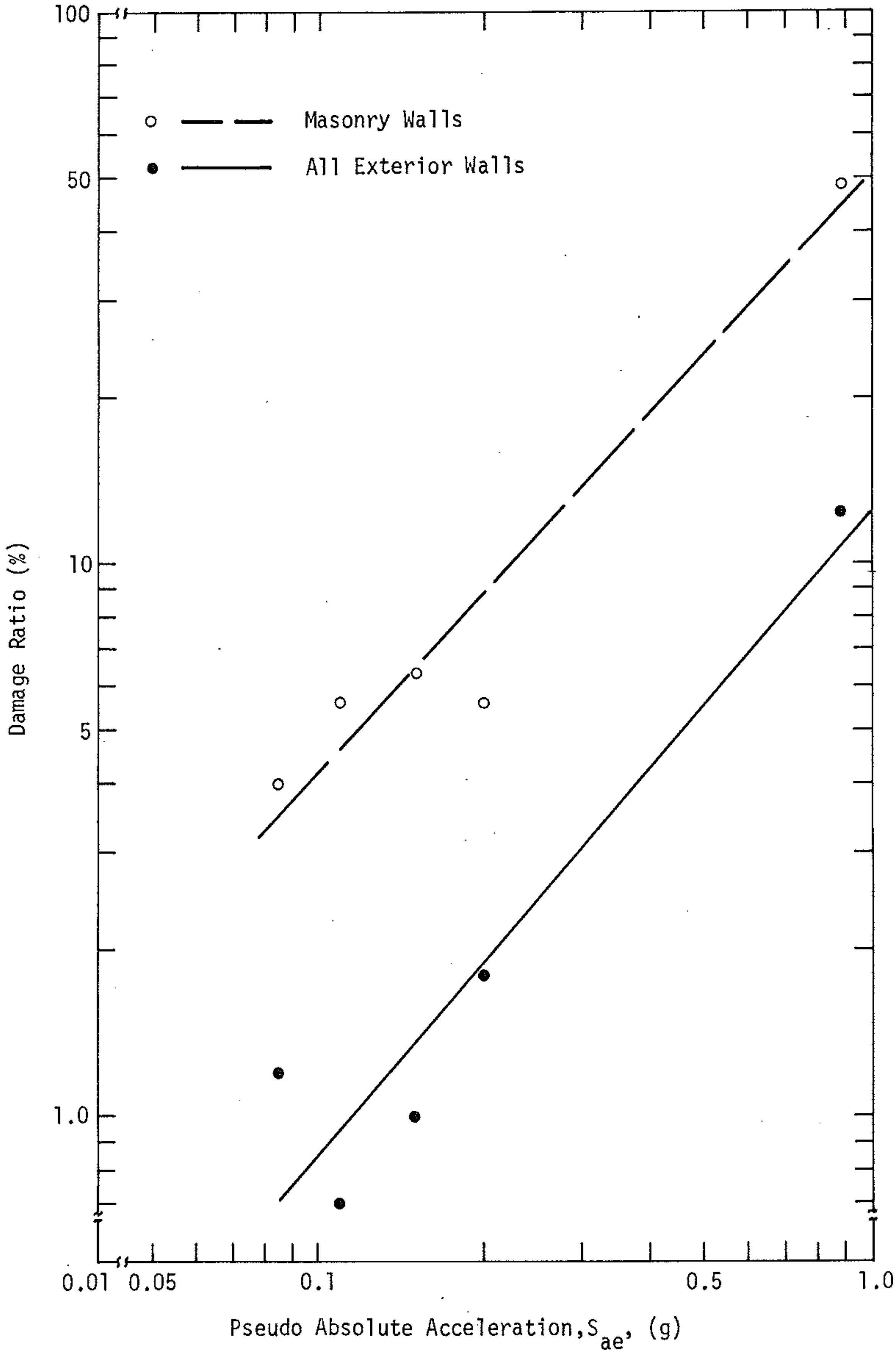

FIGURE 18 DAMAGE RATIO FOR MASONRY WALLS AND EXTERIOR WALLS VS SPECTRAL INTENSITY

can be concluded that nonmasonry walls have higher damage thresholds than masonry walls.

D. Foundations

Damage data for foundations were sparse. Therefore no distinction by type was made; only overall foundation damage was considered in this analysis.

The foundation damage ratio is defined as:

$$DR = \frac{\text{Number of Buildings with Damaged Foundations}}{\text{Number of Buildings}}$$

Damage ratios for foundations plotted against spectral intensity are given in Figure 19. The figure shows that foundation damage is not serious for the range of spectral intensity included in this investigation.

E. Windows

It is recognized that during ground motion excitation, windows are damaged in varying degrees. Damage to windows is usually the result of excessive stress caused by skewing of window frames. The RULISON event did not cause damage to an adequate number of windows to yield meaningful statistical motion-damage relationships, and therefore window damage data were not analyzed.

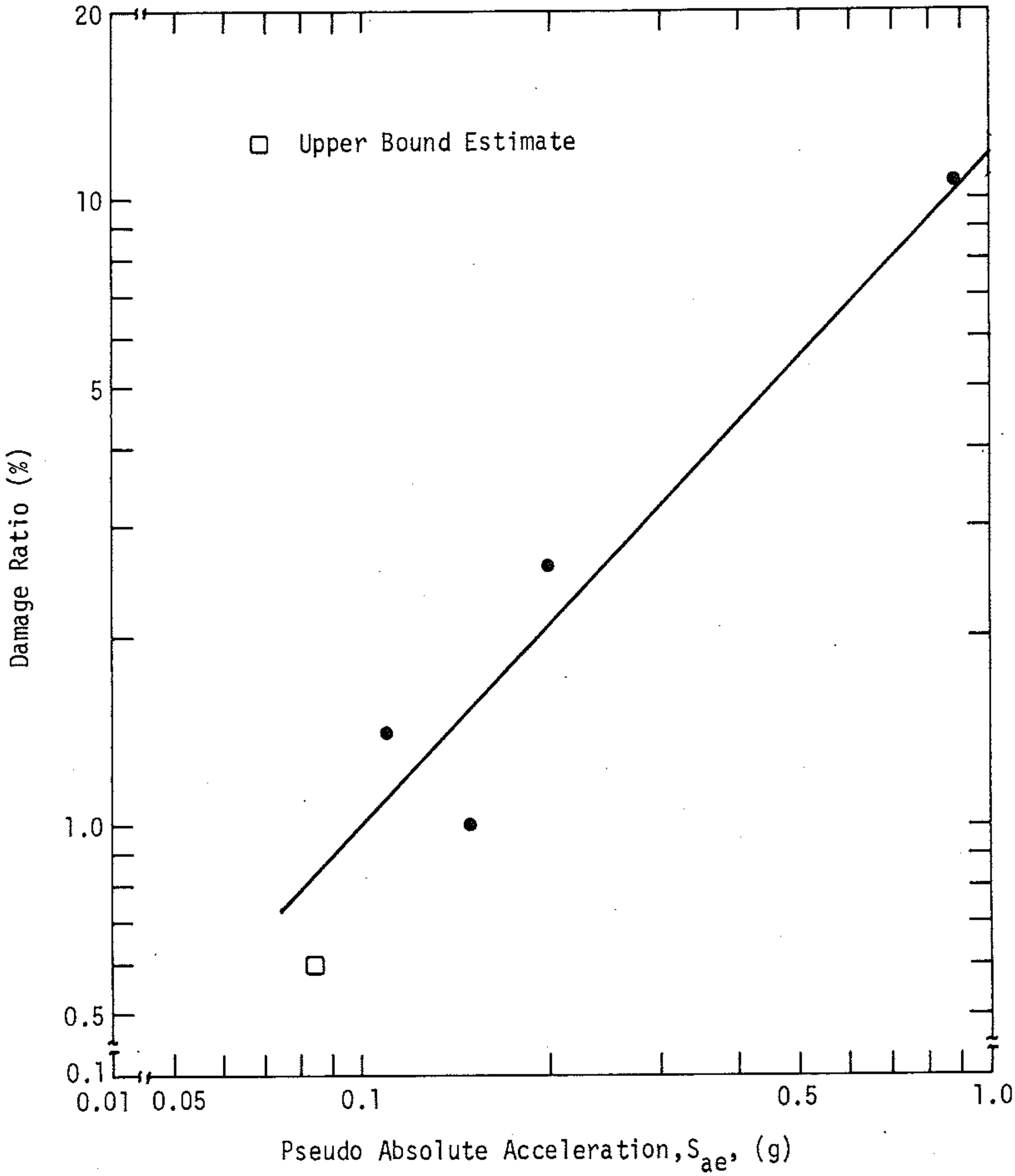

FIGURE 19 DAMAGE RATIO FOR FOUNDATIONS VS SPECTRAL INTENSITY

V. SUMMARY AND CONCLUSIONS

For this study, ground motion and low-rise building damage data from the RULISON underground nuclear gas stimulation experiment were appropriately synthesized, and regression analyses were conducted to derive motion-damage relationships for the most frequently damaged low-rise building components.

Summaries of the motion-damage relationships derived are shown in Figure 20. The figure shows the damage ratio variations with spectral intensity for the low-rise building components: chimney, interior wall, exterior wall, and foundation. For reference, the damage ratio variation with spectral intensity for overall building damage ratio which includes all types of damage is also given. To obtain these damage ratios, the number of damaged buildings, the number of buildings with interior wall damage, the number of buildings with foundation damage, and the number of buildings with exterior wall damage were normalized with respect to the total number of buildings; the number of buildings with chimney damage were normalized to the number of buildings with chimneys. The spectral intensity values were obtained by averaging the appropriate 5% damped pseudo absolute acceleration spectra over the period band 0.05 to 0.2 seconds.

Although the regression lines shown in Figure 20 have been derived from a limited number of sample points, they provide useful information concerning the relative damage susceptibility of particular low-rise building components. The figure shows that foundations are damage-resistant elements compared with chimneys and interior walls (mostly plaster coated). Chimneys sustain less damage than wall components at low spectral intensities ($S_{ae} < 0.25g$), but the chimney damage ratio increases rapidly in the moderate spectral intensity range ($0.25g < S_{ae} < 1.0g$).

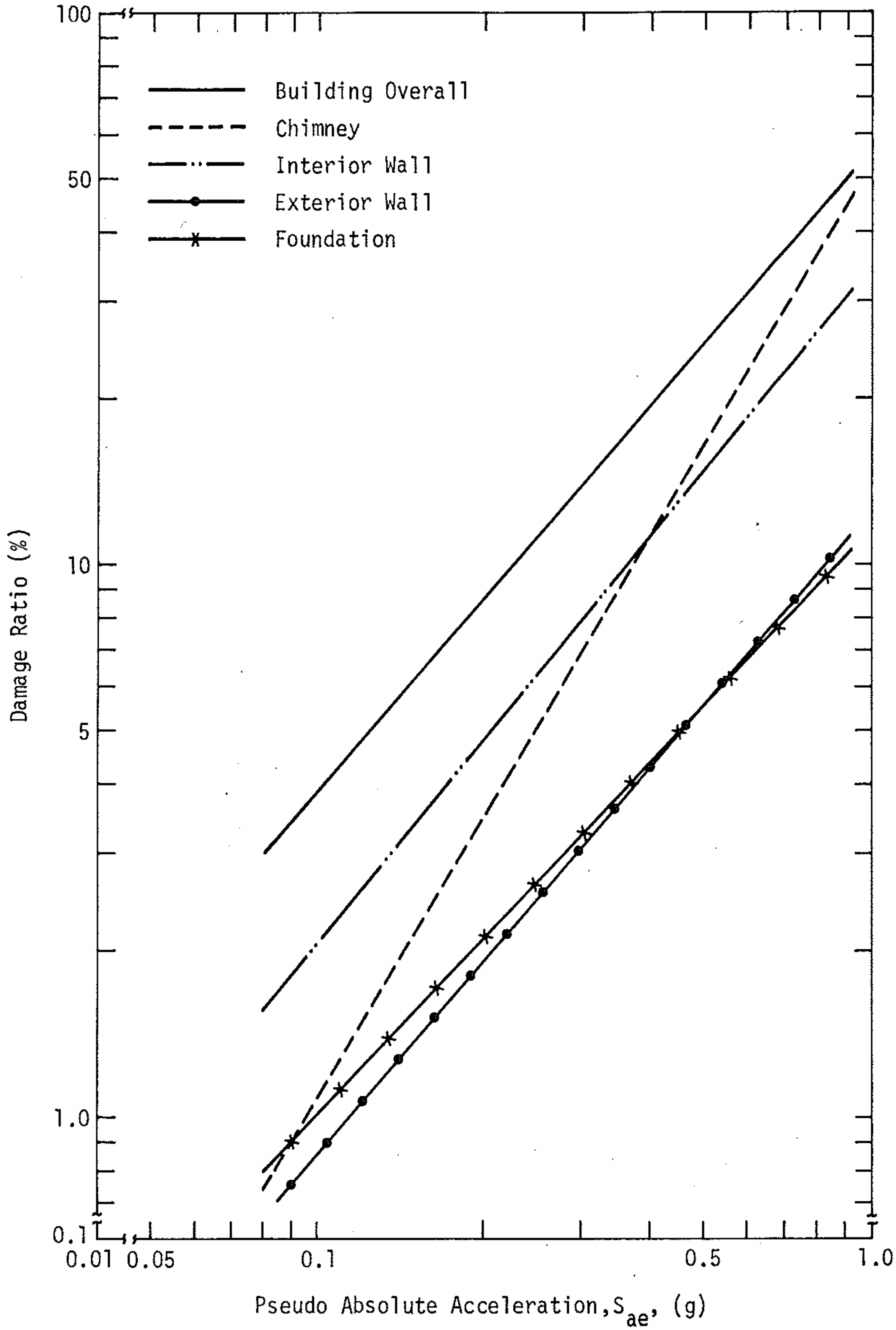

FIGURE 20 DAMAGE RATIOS FOR VARIOUS BUILDING COMPONENTS VS SPECTRAL INTENSITY

Because of the significance of and the potential hazard resulting from chimney damage at spectral intensities of $S_{ae} \rightarrow 1.0g$, more detailed study of chimney damage was performed. Correlation results indicated that for the same spectral intensity, the damage ratio for uncapped chimneys is higher than for capped chimneys. The study also indicated that chimney damage increases with the increase of chimney height above the roof line.

It is noteworthy that because Colorado is located in a Uniform Building Code (UBC) seismic Zone 1, reinforcement and lateral anchorage are not required for chimneys in wood-frame residential buildings. It is likely that few chimneys included in this study were reinforced or laterally restrained. It is most probable that this factor will have a significant effect on motion-damage relationships for chimneys.

Although the size of the data sample was limited, the qualitative conclusions made concerning the relative damage susceptibility of the various building components are expected to be applicable to other locations where the characteristics of the existing buildings are similar to those of the Project RULISON area.

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